

ENERGY DEPENDENCE OF FATIGUE-ENHANCED PHOTOEMISSION

Otto Buck
Science Center, Rockwell International
Thousand Oaks, California

This is a progress report on the subject of fatigue-enhanced photoemission. In our studies on fatigue-enhanced photoemission, the ultimate goal is to see whether or not the photoyield can be used as a tool to uniquely define the early and later stages of fatigue on structural materials. This yield results in an electron current off the specimen.

It seems to be customary now in the literature to call this current "exo-electrons", although this term was used earlier for non-stimulated electron current only¹. We should clearly distinguish between non-stimulated and photo-stimulated "exo-electrons". The intensity of the non-stimulated effect is much smaller than it is for the stimulated one. All our work is done using the photo stimulation in which an outside light source and a monochromator for energy selection are used.

A variety of mechanisms for stimulated emission have been proposed, such as:

- 1) Release of stored energy
- 2) Change of the work function of the metal or metal oxide
- 3) State of the internal stress
- 4) Formation of cracks
- 5) Exposing fresh metal surface
- 6) Change of surface roughness

At the time we began with our work, we became aware of the surface roughness studies by Endriz and Spicer^{2,3} at Stanford. They looked at the photostimulated yield on relatively smooth aluminum specimens with the rms roughness in the range of a few Angstroms to about 25 Å. The yield changed markedly over the roughness range they had available. We thought that this was a very attractive idea and thus included this possibility in our list of mechanisms. Since we concentrated mostly on this roughness effect, let me briefly outline the Endriz and Spicer ideas. It is well known that oscillations of surface charges on the metals or alloys do exist. It is further possible to couple incident photons to the oscillations of surface charges if a grating exists on this surface. These oscillations can decay by transferring their energy to a single electron, ejecting it from the metal and contributing to the photoyield.

This model may be described by the dispersion curves, shown in Fig. 1. The straight line in this figure represents the ω - k curve for the incident radiation. The dispersion curve for the surface charge oscillations

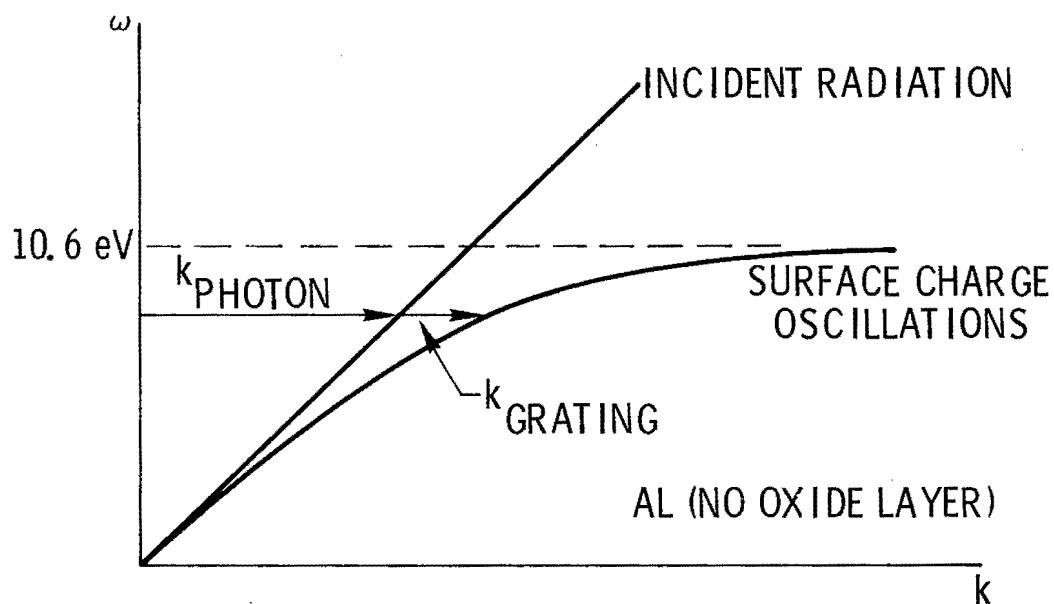


Fig. 1. Dispersion curves of Incident Radiation and Surface Charge Oscillations for clean Aluminum.

approaches an asymptotic value of 10.6 eV. In order to be able to couple the incident radiation (with wave vector $k_{\text{surface charge}}$), a grating with wave vector k has to be present on the surface. The photoyield can be enhanced then under the condition

$$k_{\text{photon}} + k_{\text{grating}} = k_{\text{surface charge}} \quad (1)$$

The asymptotic value of 10.6 eV for surface charge oscillations is only true for pure aluminum with no oxide layer on the surface of the metal. If an oxide layer is present, the dispersion curve of the surface charge oscillations is dramatically changed⁴, as shown in Fig. 2. As the oxide layer thickness increases the asymptotic value is decreased. Thus for a given roughness on the surface, the frequency of the incident radiation in the presence of an oxide layer has to be lower than the clean surface value to fulfill the resonance condition Eq. (1). Thus, we expect shifts in the photoyield vs. incident frequency curve as the oxide thickness and the roughness (due to fatigue) are changed. To observe these shifts is the goal of the present studies.

A schematic of the equipment is shown in Fig. 3. The light source is a hydrogen lamp. Frequency selection of the incident radiation occurs with a monochromator which also focusses the light on the specimen. The specimen is of the cantilever type. On one side it is firmly held by the manipulator. The other side of the specimen is flexed by an air-driven motor. The emitted electrons can be energy analyzed by a converted 4 grid LEED optics. The high-vacuum chamber ($\approx 10^{-9}$ torr) also contains an electron gun for Auger analysis of the surface and an argon sputtering gun to obtain clean surfaces (both guns are not shown). The specimens are made out of commercially pure aluminum (Al 1100) and are, at the beginning of the fatigue experiments, either in a well annealed or in a highly workhardened state.

Figure 4 shows one of our early results. The photoyield is given as a function of the energy of the incident radiation for 1100 aluminum in the initially workhardened state with an oxide layer of about 120 Ångstroms on the specimen surface. The state of the fatigue is given by the parameter "cycles". The term 0 cycles indicates no fatigue of the material has occurred, while 4×10^3 cycles is very close to fatigue failure of the specimen. A peak in the photoyield at about 5 eV grows with the number of fatigue cycles applied to the specimen. At the high energy side of the yield curves, however, the yield drops with the number of fatigue cycles applied. This data, incidentally, has not been corrected for variation in detector response over this frequency range. We are interested in the fatigue dependence and the trends are shown in Fig. 4.

The low energy part of these yield curves shows the features as would be expected from the roughness model by Endriz and Spicer. The peak increases as fatigue induced roughness increases. A peak position of 5 eV is relatively low with respect to Endriz and Spicer, however; they found their peak to be at about 8 eV on an oxide-free surface. We have to remember

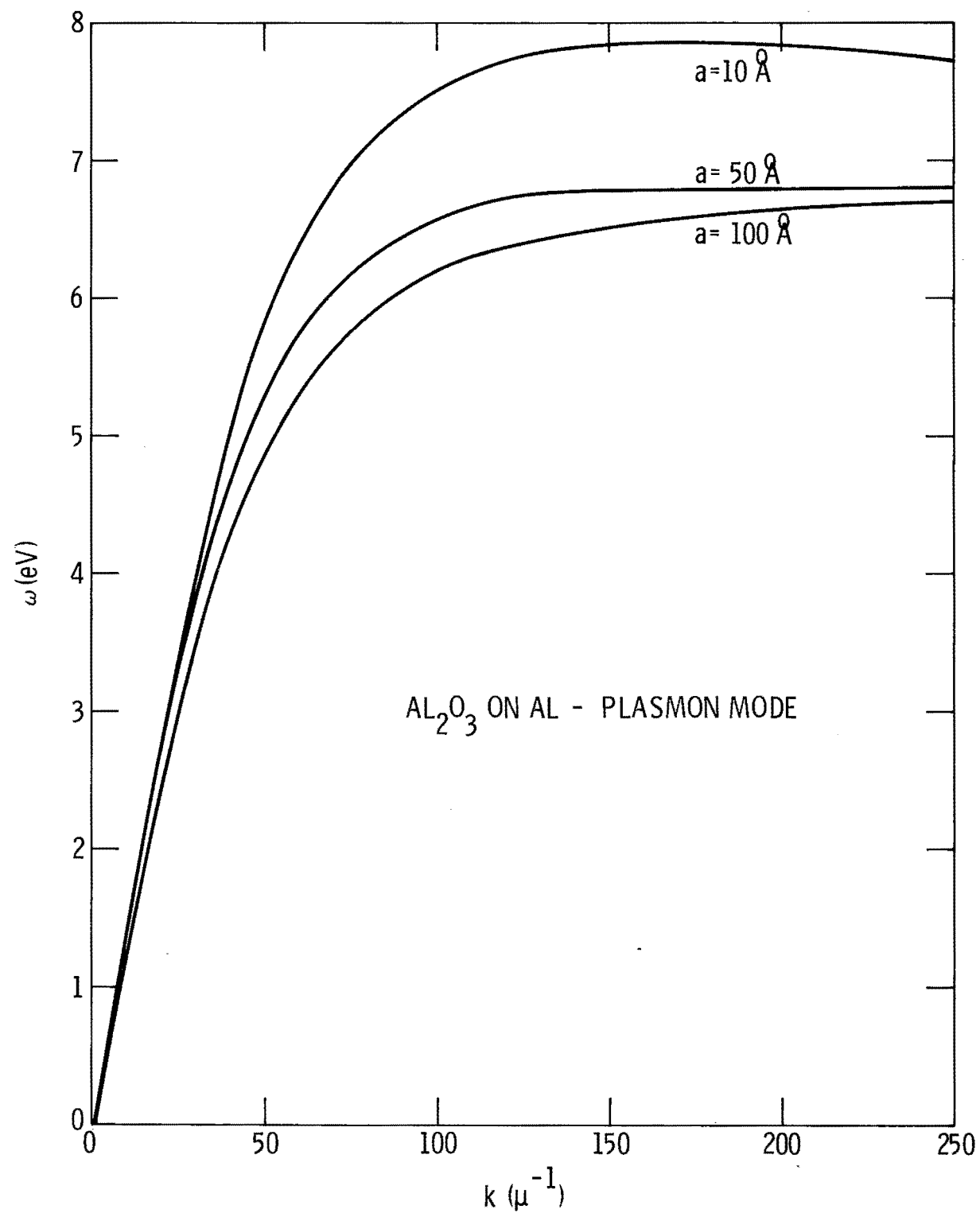


Fig. 2. Dispersion curves of Surface Charge Oscillations for Aluminum coated with an oxide layer (3 thicknesses).

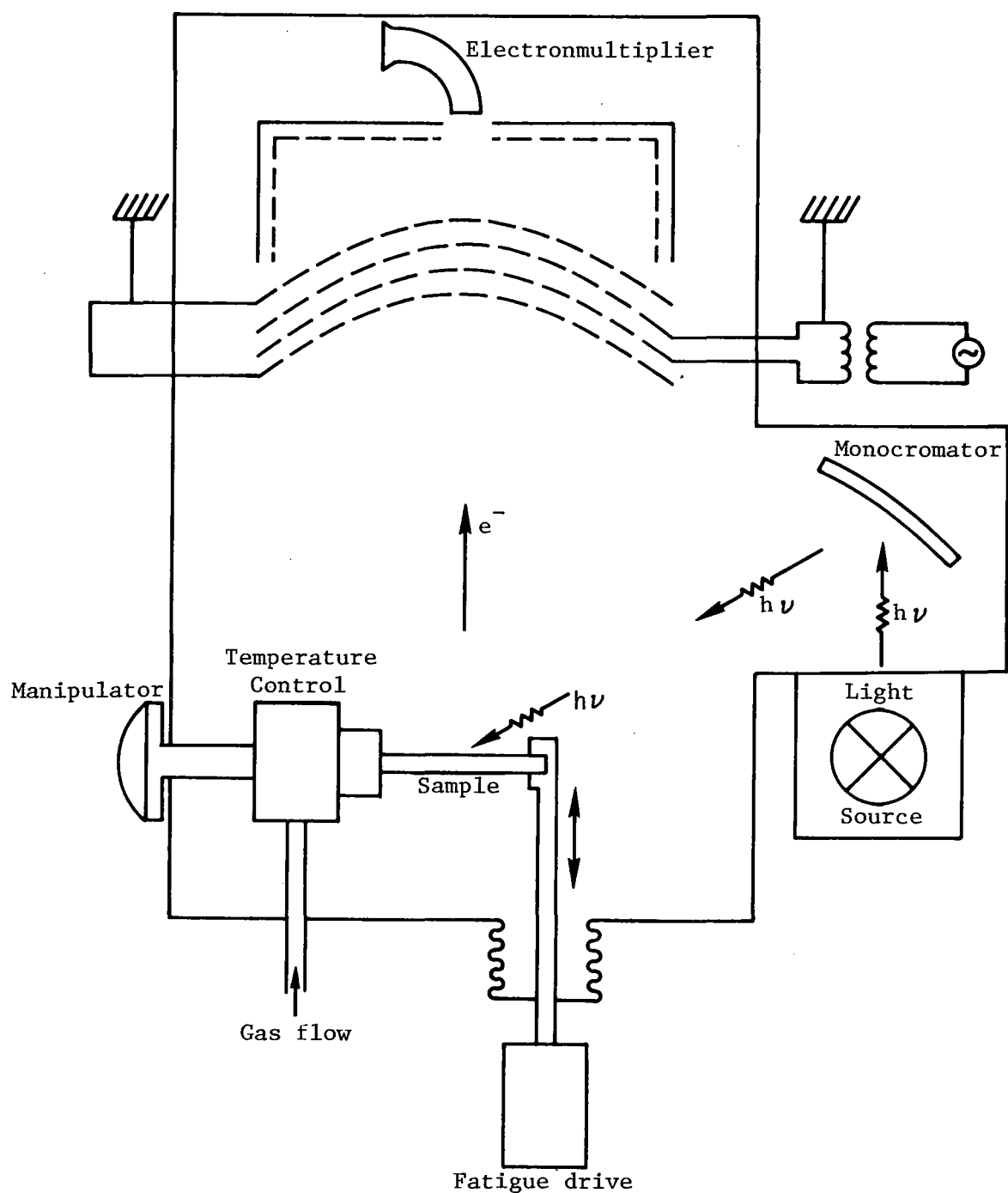


Fig. 3. Photo stimulation of Exo-electrons during fatigue. Exo-electrons are energy analyzed for a wide range of frequencies ν . Equipment also contains Ellipsometry, Auger Electron Analyzer and Ion Sputtering Gun.

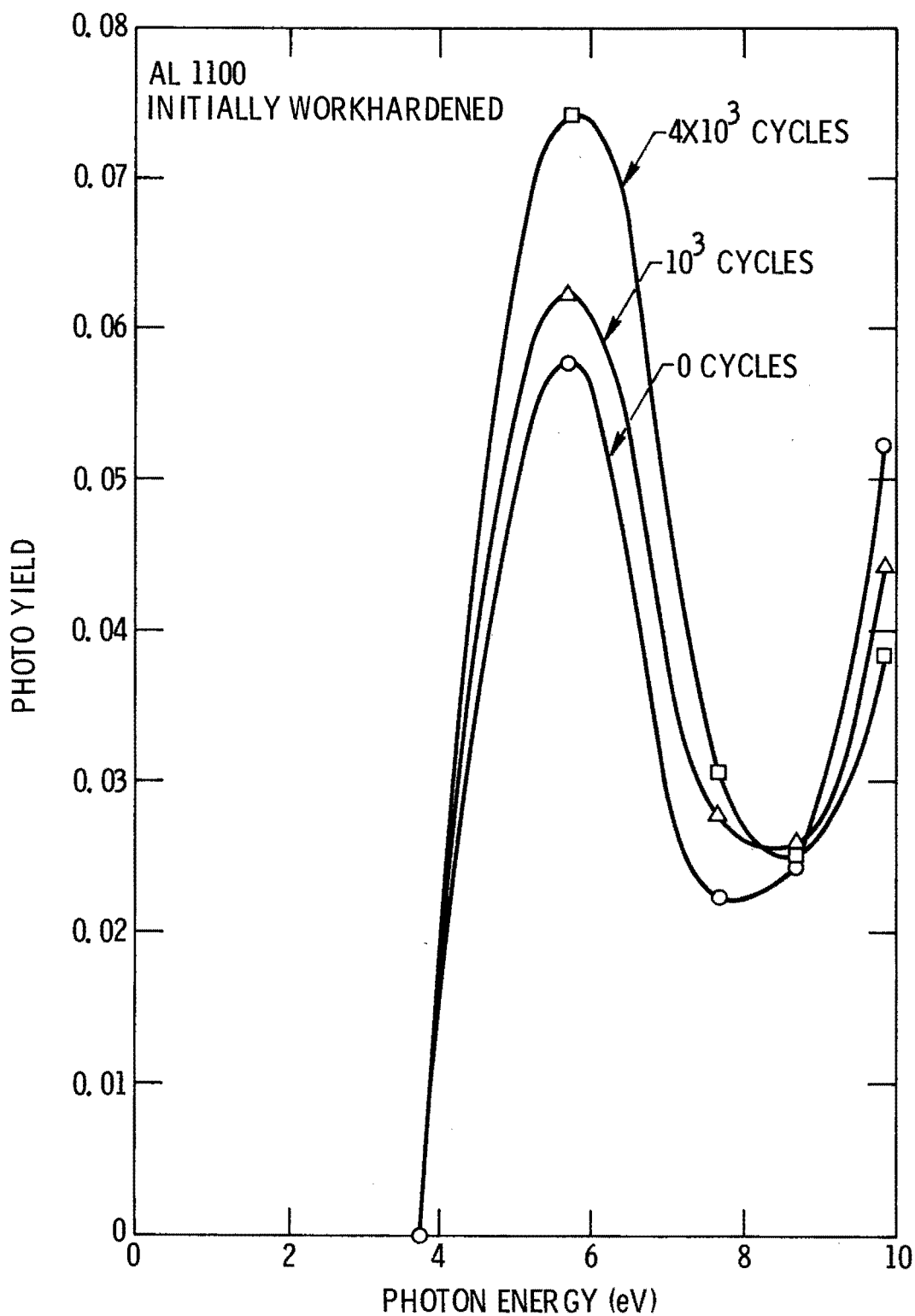


Fig. 4. Photoyield as a function of incident. Photo Energy at various states of fatigue.

that the peak position is very sensitive to the oxide layer thickness (see Fig. 2). Since the present aluminum was covered with an oxide layer of $\approx 120 \text{ \AA}$, the shift to the low value of 5 eV can easily be explained to be due to the oxide.

The decrease of the yield with increasing fatigue at the high energy side of the yield curve comes as a surprise. The high energy photoyield is probably due to interband transitions in the oxide. How these are affected by fatigue is not understood at all at the present time.

As shown in Fig. 5, a cross section through the specimen reveals the surface roughness as obtained at the end of the fatigue life of the specimen. Quite obvious are large microcracks, and the roughness definitely exceeds the one Endriz and Spicer have discussed.

At that point we decided that we should look at the very early fatigue stages. A material that lends itself for those studies is Al in the well annealed state. If this material is fatigued to about 1 percent of the total fatigue life, one finds a very fine grating running across this specimen which is due to dislocations breaking through the surface and forming fine slip lines in the order of several Angstroms which are bunched together in slip bands. This is shown in Fig. 6. The actual roughness in this case should be determined and compared with the data of Endriz and Spicer.

As the fatigue process is continued, say over another 10 percent of the fatigue life, extrusions-intrusions will emerge which will eventually lead to microcracks as shown in Fig. 5.

It is interesting now to compare the photoyield curves of both types of material, one in the annealed condition and the other in the fully work hardened condition. Starting out with the material in the annealed condition, the photoyield changes particularly fast during the first few percent of the fatigue life (see Fig. 7). At the same time the stress level increases the most (as is indicated in Fig. 7 top). This is exactly that part of the fatigue life where development of the slip line grating is observed (Fig. 5). On the other hand, the fully work-hardened material shows the biggest change in photoyield in the later stages of the fatigue life (see Fig. 7). This material does not show the fine grating at the beginning of fatigue. On the other hand, this material does show a strong drop in yield stress as indicated in Fig. 7.

After about 5 percent fatigue, the first indications of extrusions-intrusions and then later microcracks occur, leading to, in that particular case, an increase in photoyield. It is speculated at the present time that the long wavelength roughness due to extrusions and intrusions is covered with a short wavelength roughness due to individual dislocation steps at the surface causing the photoyield to rise.

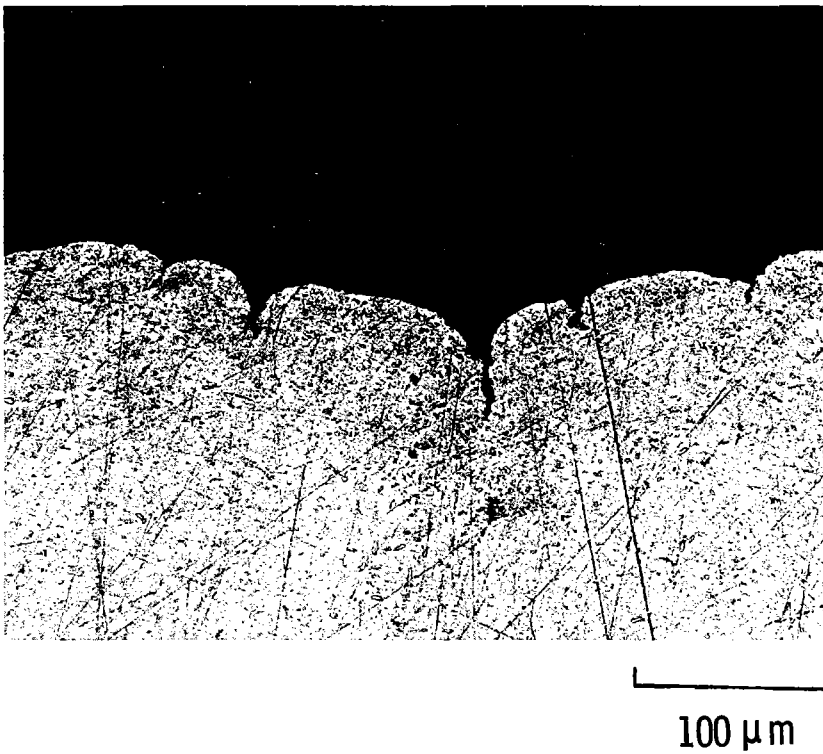


Fig. 5. Surface roughness of a fatigued Aluminum Specimen (End of fatigue life).

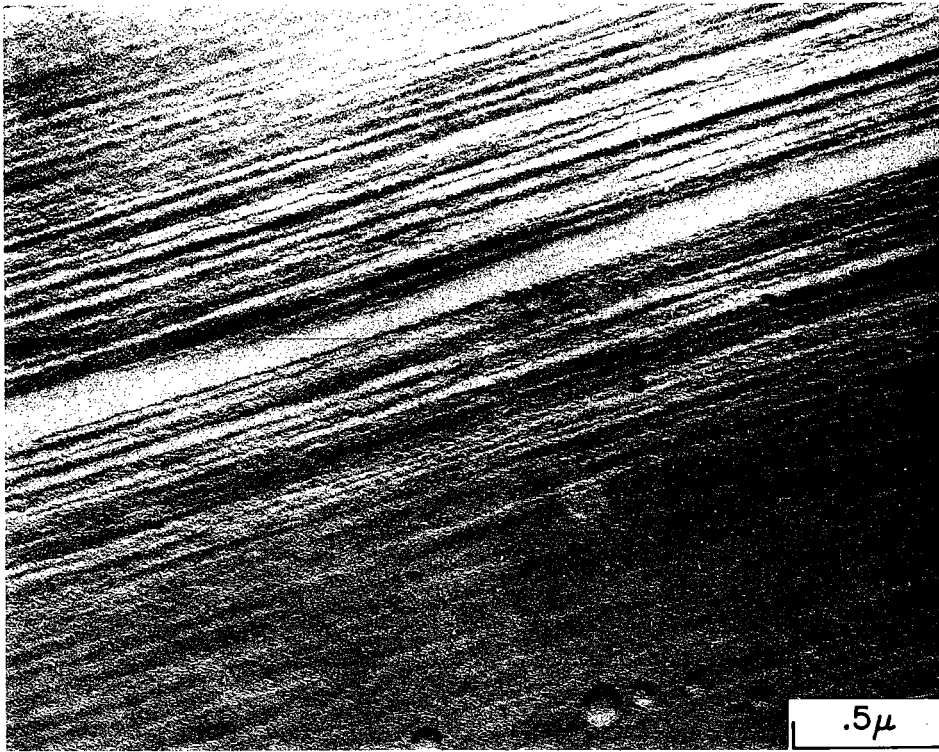


Fig. 6. Surface replica of annealed aluminum specimen (1% of total fatigue life).

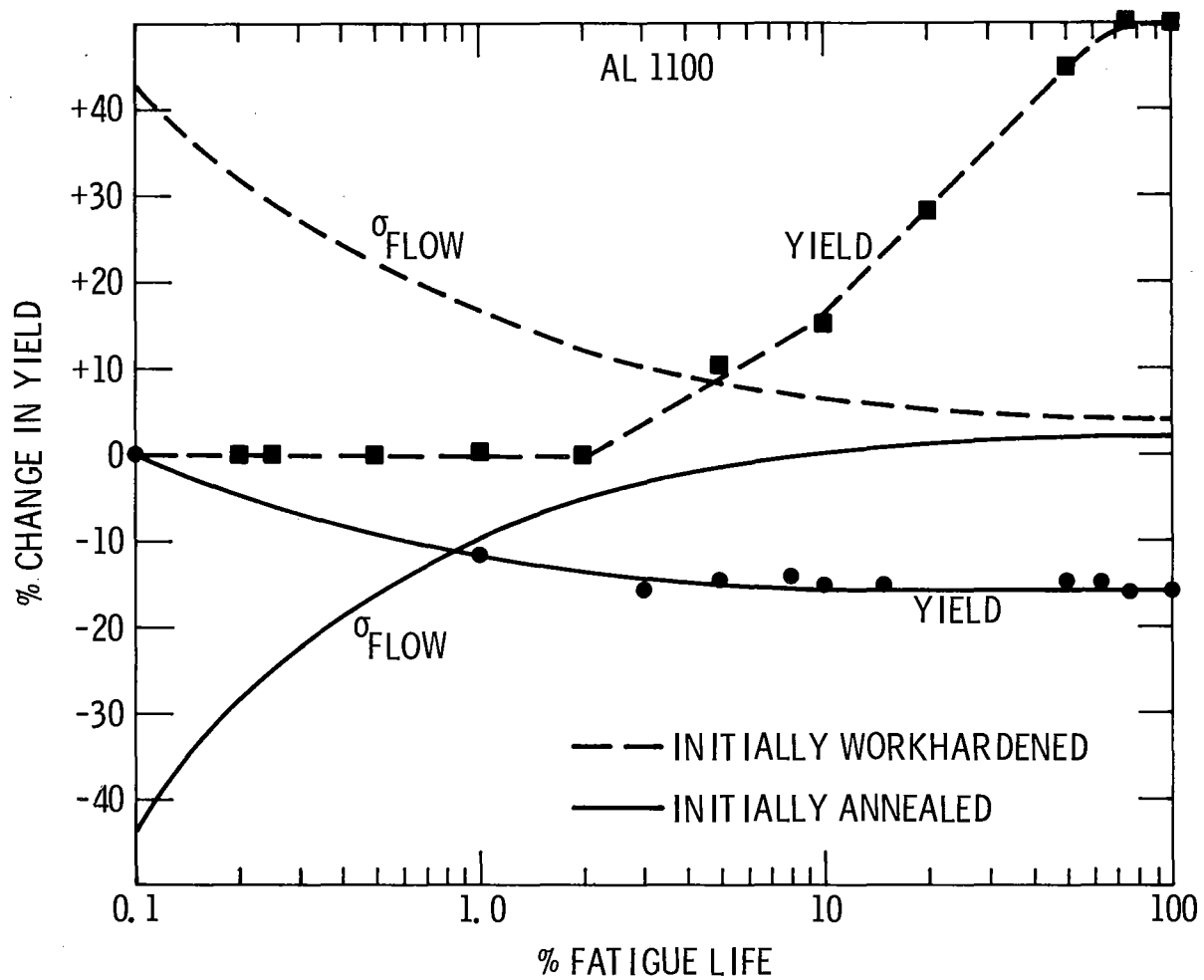


Fig. 7. Photoyield and flow stress as a function of fatigue for an initially annealed and an initially work-hardened Al specimen.

Thus, we believe, that from the roughness point of view, the fine slip steps that are produced on a material in the annealed condition are responsible for the photoyield, similar to the results of Endriz and Spicer on the influence of roughness on photoyield.

There is another interesting sidelight here. Going back to the work hardened material, which shows a drop in flow stress at the beginning of the fatigue, the photoyield doesn't change during that period of time. It is well known that the dislocation arrangement, and thus the internal stress level due to elastic distortion around the dislocations, changes particularly fast during these first few percent of the fatigue life. However, no change in the photoyield was observed on this material. Thus, we do not believe that the internal stresses (due to dislocations) are responsible for the change in photoyield.

If the roughness model, which is affected by surface oxide, is correct, one has to expect that sputtering should yield a peak in the photoyield higher in energy than for an oxidized surface. These measurements are underway.

Some work on the energy analysis of photo-stimulated exo-electrons has been done also. The major purpose of such experiments is to find out whether or not an effect on the work function due to fatigue could be the cause for fatigue enhanced photoemission. We have not seen any significant effects of fatigue on the energy distribution as of yet (Fig. 8). Further work on this subject is in progress too, however.

In conclusion, I should say that most of our experimental results obtained so far seem to be in agreement with the Endriz and Spicer model applied to fatigue enhanced photoemission. Further work is necessary, however. Also, I should thank Dr. Bill Pardee from the Science Center for his contributions to this paper.

References:

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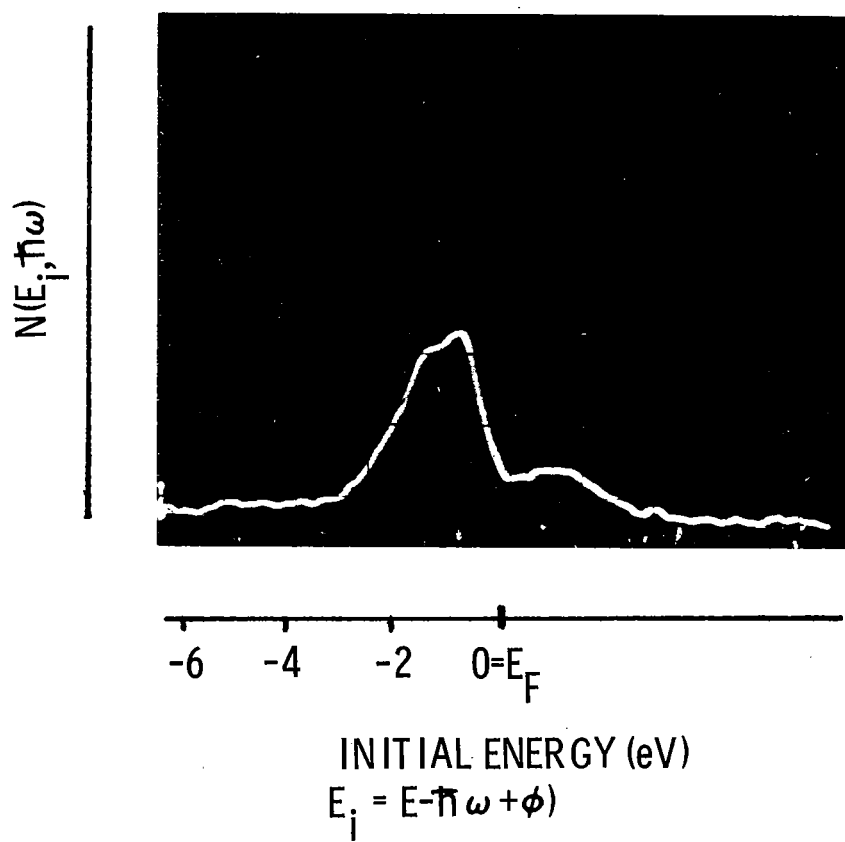


Fig. 8. Energy analysis of photo-stimulated Exo-electrons.

DISCUSSION

DR. TIEN (Henry Krumb School of Mines, Columbia University): Are there any questions?

DR. BRUCE THOMPSON (Science Center, Rockwell International): Isn't there a dark emission?

DR. BUCK: Yes. That's right. That's what I called the "nonstimulated emission". Other people call it "dark emission"; that's correct.

DR. BRUCE THOMPSON: That could not be explained by Endriz and Spicer?

DR. BUCK: No.

DR. TIEN: Otto, would you care to tell us about some of the advantages and disadvantages of either, as far as you know. I know that all of the work is in progress.

DR. BUCK: You mean stimulated versus non-stimulated effects?

DR. TIEN: Yes.

DR. BUCK: The photostimulated effect seems to have the advantage that, first of all, one obtains a larger signal. The exo-electron currents from the specimen are easily detectable. Secondly, as far as we are concerned, we have the possibility of varying the stimulating energy. Perhaps there are stimulating energies which work much more to our advantage to detect fatigue damage than are expected at present. Perhaps there are energies that are--and particularly on the high frequency side--that are more indicative for the conditions towards the end of the fatigue life, and other frequencies might be more indicative for events at the very early fatigue life stages. We don't know, but that's our driving force.

DR. GERRY GARDNER (Southwest Research Institute): I did not grasp the point you were trying to make about the role of the oxide, either in the talk or the remarks just made. Now, is the photoemission from a clean unoxidized surface distinctly different and governed by mechanisms distinctly different from what it is when there's an oxide coat on it?

DR. BUCK: It's a very complicated subject. I concentrated more on the roughness induced effects. In general, we found that the oxide layer tends to decrease the photoyield in the unfatigued state. However, the changes in yield as a function of fatigue seem to be larger. Above about 8 eV, the oxide effects seem to be particularly important and the photoyield increases very strongly in this high energy range. In the low energy range, where roughness seems to dominate, the yield increases with fatigue; in the high energy range (8 eV) the photoyield seems to decrease with fatigue. Thus we definitely have two superimposed

processes. One is the roughness process (mainly active below 8 eV) and the other is what seems to be an oxide effect (mainly above 8 eV). We are not quite sure right now to separate out those two effects quite clearly.